Soil & Tillage Research 107 (2010) 17–25

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Soil quality indicator response to tillage and residue management on semi-arid Mediterranean cropland

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ARTICLE INFO

Article history:
Received 6 April 2009
Received in revised form 9 February 2010
Accepted 11 February 2010

Keywords:
Soil quality
Mediterranean soils
Conservation tillage
Minimum data set

ABSTRACT

No-tillage (NT) practices for rainfed cereal production in semi-arid Mediterranean soils can conserve water and increase crop productivity, but producers are reluctant to adopt NT because of potential increases in penetration resistance and bulk density. We hypothesized that understanding soil quality could encourage NT adoption, but methods for selecting and assessing soil quality indicators needed to be developed for this region. Our objectives were to (1) identify the most sensitive indicators for evaluating long-term tillage and residue management within this region using factor analysis, and (2) compare soil quality assessment using those indicators with traditional evaluations using changes in water retention, earthworm activity and organic matter stratification ratio. Several soil physical, chemical, and biological indicators were measured within conventional tillage, minimum tillage, and NT (with and without stubble burning) treatments that represent a wide agro-climatic area in NE Spain. Sampling depth and management treatments significantly affected several indicators when evaluated individually and collectively. Principal component analysis identified three factors that accounted for 75 and 85% of the variation in soil measurements for 0–5- and 5–15-cm depth increments. Only two factors per depth showed significant differences among the four treatments. For both depth increments, one factor grouped soil physical attributes, and the other organic matter and biological properties. The indicators with the greatest loadings were identified as the most sensitive in each factor. These were penetration resistance, particulate organic matter (POM) and total organic matter within the 0–5 cm layer, and aggregate stability and POM within the 5–15-cm increment. Factor scores were positively correlated to soil water retention, earthworm activity and organic matter stratification, which were all greater in NT, regardless of stubble management. We conclude that (1) multivariate analyses are useful for selecting appropriate soil quality indicators, and (2) that adopting NT on Mediterranean semi-arid cropland can have several positive effects on soil quality within this region.

1. Introduction

Semi-arid soils in the Mediterranean basin generally have low organic matter levels because of historical exploitation, low carbon inputs, and a climate that favors mineralization. In Eastern Spain and other similar areas, soils also frequently have high amounts of carbonates and in some cases excess soluble salts that can significantly affect their physical properties (Muneer and Oades, 1989; Szabolcs, 1989). Biological activity, as expressed by net respiration and decomposition rates is also hindered by dry soil and warm climatic conditions (Zhou et al., 2006).

For rainfed agriculture in this area, water availability is the primary factor controlling crop productivity, so any soil and crop management practices that can enhance soil water storage and availability are likely to increase yield and overall productivity. No-tillage (NT) and crop residue retention have been shown to retain more water in these semi-arid Mediterranean soils, not only because of reduced evaporation (Lampurlanés and Cantero-Martínez, 2006), but also because no-tillage often results in the development of a new and more extensive pore system that enhances soil water holding capacity (Bescansa et al., 2006a). Tillage is often justified for these soils because, as reported in other areas (Arrouays et al., 2002), producers are concerned that without it, compaction often results in higher bulk densities and increased penetration resistance, especially in the upper few centimeters (Schjønnning and Rasmussen, 2000; Bescansa et al., 2006b). Perhaps by developing criteria for assessing soil quality, producers will be able to understand all aspects of soil management and thus be more willing to adopt NT practices and gain the water conservation, soil organic matter, and crop yield benefits of those practices (Bescansa et al., 2006b).

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0167-1987/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2010.02.003

Soil quality has been defined as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin, 1994). Its assessment is best viewed as an integrative indicator of sustainable land management, as it often reflects environmental quality, food security, and economic issues (Larson and Pierce, 1994; Lal, 1999; Herrick, 2000). With soil as a multifunctional resource (Singer and Erwin, 2000), soil quality assessment must be approached considering both the ecosystem characteristics and primary purpose for which the evaluation is being made (Karlen and Stott, 1994; Andrews et al., 2004). With regard to agricultural production and adoption of NT for enhanced water conservation, a high quality rating equates to having high productivity with improvement in soil or as little environmental degradation as possible (Govaerts et al., 2006).

Soil quality assessment must account for both inherent and dynamic soil properties and processes and must be holistic, accounting for all soil processes and interactions within soils (Karlen et al., 2003). For a specific site, assessment will be influenced by many factors including tillage, crop rotation, animal- or green-manure applications and other management factors, as well as climate and soil type. Ideally soil quality should be easy to measure, able to reflect changes in soil functions, sensitive to variations in management, and accessible to as many users as possible (Shukla et al., 2006). Furthermore, the site-specific nature of soil quality may actually require different soil property measurements depending upon the specific agroecosystem for which the assessment is being made (Govaerts et al., 2006; Rezaei et al., 2006; Shukla et al., 2006; Yemefack et al., 2006; Marinari et al., 2006).

The first step toward soil quality assessment is the selection of soil quality indicators (SQI), that is the soil properties and processes that will provide a minimum data set for evaluation (Andrews et al., 2004). Care must be taken to ensure that these SQIs accurately represent both human-induced and natural or inherent changes in the soil for which the evaluation is being made (Wienhold et al., 2004; Yemefack et al., 2006). With regard to assessing NT in cereal rainfed systems in Mediterranean semi-arid areas, enhanced structural stability and earthworm activity (Virto et al., 2007), organic matter and calcium carbonate stratification (Moreno et al., 2006) and biological status (Madejón et al., 2007) are among the indicators that would be expected to be useful for making the evaluation. However, few studies have been devoted to actually determining the minimum set of indicators for soil quality assessment in the semi-arid Mediterranean region (Zornoza et al., 2007b), and therefore, information on various SQI for this region is lacking.

The objectives for this study were (1) to identify the most sensitive SQI for evaluating long-term tillage and residue management within a semi-arid Mediterranean agroecosystem using factor analysis and (2) to compare soil quality assessment using those SQI with a soil quality evaluation using well-known indicators for that agroecosystem such as water retention, earthworm activity and the organic matter stratification ratio. We focused on rainfed cereal production systems, because they are widespread in the Mediterranean region (Monfreda et al., 2008), and yet poorly studied in relation to soil quality assessment.

2. Materials and methods

2.1. Experimental site

The experimental site was located in Olite (Navarre, NE Spain) (42°27′19″N; 18°10′00″W; 402 m a.s.l.). It has been used for demonstration purposes for more than 10 years because it is representative for the type of soils and cropping systems for rainfed cereal production in the Upper Ebro Valley (Bescansa et al., 2006b). The soil in this site is a fine-clayey Calcic Haploxerept (Table 1, Soil Survey Staff, 2003). Haploxerepts are abundant throughout the Mediterranean basin, covering more than 70,000 km^2 in Spain alone (IGN, 2006) and frequently being devoted to agriculture. In the Upper Ebro Valley in Navarre, where the study site is located, agricultural rainfed land covers more than 116,000 ha with 85% of the area devoted to cereal cropping (Gobierno de Navarra, 2009). Similar percentages are expected in other rainfed Mediterranean cropland areas in Spain and other Mediterranean countries.

Table 1
General soil characteristics in the studied soil. Mean ± standard deviation.

Soil depth (m)	0–0.30	0.30–0.75	0.75–1.05
Particle size distribution ($g\,kg^{-1}$)			
Sand (50–2000 μm)	171 ± 45.6	315	277
Silt (2–50 μm)	411 ± 23.3	322	328
Clay (<2 μm)	413 ± 18.1	363	395
Bulk density ($mg\,m^{-3}$)	1.52 ± 0.10	1.76	1.79
$CaCO_3$ ($g\,kg^{-1}$)	326 ± 16.1	360	335
pH (water)	8.29 ± 0.02	8.50	8.20
Electrical conductivity ($dS\,m^{-1}$)	0.23 ± 0.06	1.52	4.54
Cation exchange capacity ($cmol\,kg^{-1}$)	19.7	20.7	21.6

The site had been cultivated using conventional tillage and used for cereal production for decades. The climate in this portion of Spain is described as being Dry subhumid (C1B′2db′4), according to the classification of Thornthwaite (1948). Mean annual evapotranspiration is 740 mm and mean monthly temperature is 13.5 °C. The average annual precipitation is 525 mm with 18% being received during the summer (July–September). This makes this site representative of the climate in a wide area around the Mediterranean basin.

2.2. Experimental design

The experimental design was a randomized block with four replications. Plots were 9 m × 24 m in size. A total of six soil and crop residue management practices were included in each block, four of which were evaluated to determine soil quality effects. They were the four more common practices for rainfed cereal production in the region: conventional tillage (CT), minimum tillage (MT), no-tillage (NT) and no-tillage with stubble burning (NTSB). Stubble burning under NT was included as a treatment because it has traditionally been used in semi-arid areas for pest and weed control and to facilitate soil management (Virto et al., 2007), and because until recently it was the common practice in the studied area. Conventional tillage consisted of mouldboard ploughing (0.25 m deep) in late summer, followed by secondary tillage with a harrow for seedbed preparation before seeding (late October). Crop residues were incorporated into the arable layer during tillage. Seeding was accomplished using a coulter-seeder. Minimum tillage consisted of chisel ploughing (0.15 m deep) and secondary tillage and seeding as for CT. A direct seeder that opened a seed-furrow 30–50 mm deep, was used for NT and NTSB. For NTSB, stubble was burnt with a low-intensity fire just before seeding. Barley (*Hordeum vulgare* L. var. Tipper) was planted each year at a sowing rate of 158 kg/ha. Nitrogen and P fertilization were similar for all treatments, averaging 100–27–0 kg N–P–K ha^{-1} $year^{-1}$. Superphosphate was used as basal dressing in September every other year. Urea was used every year for N fertilization.

2.3. Soil sampling

For this study, soil samples were collected 10 years after the original field experiment was initiated. Disturbed and undisturbed samples were collected for the various analyses. Disturbed soil samples were collected for the 0–5- and 5–15-cm depth using an Edelman type auger (Ø = 5 cm). Five subsamples were collected per plot for each depth increment and combined to obtain a composite sample for chemical and physical analyses. Immediately after sampling, a portion of the composite soil sample was gently pushed through an 8 mm sieve. These aggregates were allowed to air dry and used to for aggregate stability determinations (see below). The remainder of the soil was air-dried and ground to pass a 2 mm sieve.

Undisturbed core samples were collected in triplicate using bevel-edged steel rings (Ø = 5 cm, total volume = 100 cm^3) for the 0–5- and 5–15-cm depth increments to determine soil bulk density (ρ_b) and for the 0–15-cm depth to determine soil water retention characteristics.

2.4. Soil analyses

Soil physical, chemical and biological properties measured for this study were selected to reflect the particularities of soil management and characteristics within the region following the approach given by Govaerts et al. (2006). We considered the most important factors limiting crop production in the area and then measured soil properties influenced by those factors.

2.4.1. Physical properties

The core method was used to determine ρ_b. Particle size distribution of ground (<2 mm) air-dried samples was determined by the pipette method using a modified Robinson pipette. Soil water retention (SWR) at matric potentials of 0 and −33 kPa was determined using undisturbed soil samples and sieved (<2 mm) soil samples were used to measure SWR at −1500 kPa, using pressure plate extractors (Soil Moisture Equipment Corp., Santa Barbara, CA). Volumetric SWR values were calculated using ρ_b. Soil available water content (AWC) was calculated from the difference in soil volumetric moisture content at field capacity (−33 kPa) and wilting point (−1500 kPa).

Dry aggregate stability was determined by placing 100 g of dry aggregates (≤8 mm) in the top of a column of sieves of 6.3, 4, 2, 1, 0.5 and 0.25 mm openings and shaking the whole in a rotary movement at 60 strokes/min for 60 s in a Retsch VS 100 device (Retsch GmbH & Co., Haan, Germany). For wet aggregate stability, a constant shower-like flux (6 L/min) of distilled water was applied from the top of the same set of sieves while sieving (60 strokes/min, 60 s). Equal initial aggregate distributions for wet and dry sieving for each sample was ensured by using a sample conditioner coupled to a divisor (Retsch GmbH & Co., Haan, Germany). Aggregate size distribution was expressed as the mean weight diameter (MWD) after dry and wet sieving. The stability of aggregates was evaluated using the ratio of wet-to-dry MWD (MWD_w/MWD_d), as proposed by Lehmann et al. (2001) and Franzluebbers (2002).

Penetration resistance (PR) was measured 6 months after seeding at 9 points per field replicate to a depth of 60 cm using a field penetrometer (Rimik CP20, Agridy Rimik Pty Ltd, Toowoomba, Qld, Australia). This instrument measures the mean vertical strength required to introduce a steel cone of 6.3 cm^2 (diameter = 1.28 cm, angle = 30°) into the soil. Measurements were done after a rainy period to avoid differences in moisture content among treatments. Measurements were recorded every 15 mm, and PR of the studied depths (0–5, 5–15 and 15–30 cm) were calculated as weighted depth averages.

Saturated hydraulic conductivity (K_{fs}) was determined in the field using a Guelph permeameter (Model 2800, Soil Moisture Equipment Corp., Santa Barbara, CA, USA).

2.4.2. Chemical properties

Total N was determined using the Kjeldahl digestion procedure. Available P was determined as described by Olsen and Sommers (1982). Exchangeable K was quantified using atomic absorbance after extraction with NH_4OAc 1N (Knudsen et al., 1982).

Soil electrical conductivity (EC) and soil pH were measured in distilled water (1:2.5). Soil pH was determined with a Crison GLP22 pHmeter (Crison Instruments, S.A., Barcelona, Spain). Conductivity was read with a Crison GLP32 conductivity meter (Crison Instruments, S.A., Barcelona, Spain). Carbonates content was measured in a Bernard's calcimeter by quantifying the CO_2 produced when attacking a soil sample (<2 mm) with HCl.

2.4.3. Organic matter and soil biological properties

Soil organic C (SOC) was determined by wet oxidation (Walkley-Black). SOC mineralization rates were determined by incubating 10 g of the ground samples from the 0 to 5 cm depth at 25 °C for 28 days. Samples were kept at 55% of their field capacity in sealed 1-L jars containing NaOH 0.2 M traps for respired CO_2. Traps were periodically titrated with standardised HCl to determine the C evolved as CO_2 (CO_2-C). We estimated the O_2 consumption rate from previous incubation studies (Virto et al., 2007), and assured aeration by opening the jars at every sampling date. For this study, we used the accumulated CO_2-C in days 14 and 28 of the incubation (CO_2-C_{14d} and CO_2-C_{28d}, respectively). After 28-days incubation, KCl 2 M extracts of the samples were used to determine the amounts of N in the form of ammonium (NH_4-N) and nitrate (NO_3-N) by absorbance measurement (Cawse, 1967; Nelson, 1983). The fraction of organic matter corresponding to particulate organic matter >53 μm in size (POM, Cambardella and Elliot, 1992) was isolated by dispersion and sieving of 10 g of air-dried soil, using a method described in Virto et al. (2007). Samples were then ground to a powdery consistency before measuring C and N (to determine POM-C, POM-N, and POM-C/N) by wet oxidation and Kjeldahl digestion, respectively.

Two soil blocks (20 cm × 20 cm × 20 cm) were taken in each plot in May (spring, physiological maturity of barley) for earthworm activity determination. Earthworms were sampled by hand-sorting and counted in the field. Individuals were weighed (fresh weight basis) in the laboratory, fixed with ethanol-formalin, and preserved in 10% formalin (Baker and Lee, 1993).

2.5. Statistical approach

Soil properties (variables) were grouped into chemical, physical and biological, for each depth increment. Prior to performing the factor analysis, multivariate statistical analysis was conducted in two steps, as in Wander and Bolero (1999) and Govaerts et al. (2006). We first ran a multivariate analysis of variance (MANOVA) to test whether there was a significant effect of our categorical independent variables (management and depth) on at least one of the physical, chemical or biological variables studied. We used Wilk's lambda and derived F statistics to test the null hypothesis of no overall management or depth effect. After this criterion was met, we ran univariate analysis of variance (ANOVA) for the different soil variables to examine for significant influences in management and depth. Only those variables for which the F statistics for soil management was significant ($P < 0.05$) were retained for further analysis.

Factor analysis was then used to group the retained variables into statistical factors based on their correlation structure. Principal component analysis (PCA) was used as the method of factor extraction (Brejda et al., 2000). To eliminate the effect of different units of variables, factor analysis was done using the correlation matrix on the standardized values of the measured soil properties, so that each variable had mean = zero and variance = 1 (total variance = number of variables; Shukla et al., 2006). We used the determinant of the correlation matrix as an indicator to identify the existence of correlations among variables.

Using the correlation matrix, principal components (factors) with eigenvalues >1 were retained and subjected to varimax rotation with Kaiser to estimate the proportion of the variance of each attribute explained by each selected factor (loadings), and by all factors (communalities). A high communality for a soil attribute indicates that a high proportion of its variance is explained by the factors. In contrast, a low communality for a soil attribute indicates much of that attribute's variance remains unexplained. Less importance should be ascribed to soil attributes with low communalities when interpreting the factors (Brejda et al., 2000).

To evaluate the effects of the studied tillage and residue management treatments on the extracted factors, factor scores for each sample point were calculated and ANOVA was performed on the new score variables. Homogeneous groups among treatments were detected using Duncan's test ($P < 0.05$, unless otherwise indicated). Only factors that differed among treatments were retained for further consideration. Soil attributes were then assigned to the factor for which their loading was the highest (Shukla et al., 2006). For each retained factor, highly weighted attributes were selected as possible SQI. We considered highly weighted as those within 10% of the highest factor loading, as in Andrews et al. (2002b) and Rezaei et al. (2006). When more than one soil attribute was included within this range, they were subjected to redundancy analysis to determine whether all or any of them were correlated, and thus could be eliminated from our list of selected SQI.

The score values of the selected factors were used to fit a multiple regression with other well-known SQI in the region (i.e. water retention ability (Bescansa et al., 2006a), earthworm activity (Virto et al., 2007), and organic matter stratification ratio (Franzluebbers, 2002), as dependent variables, and the factors as independent variables, as in Govaerts et al., 2006, to compare factors issued from the PCA to other well know SQI. All statistical analyses were conducted with SPSS 15.0 (SPSS Inc., 2007).

Table 2
Significance of management and depth on soil properties groups based on multivariate Wilk's lambda *F* statistics.

Soil properties	Factor		
	Management (*M*) (tillage + residue)	Depth (*D*)	$M \times D$
Physical	<0.0001	0.001	0.125
Chemical	<0.0001	<0.0001	0.062
Organic matter and biological	<0.0001	<0.0001	<0.0001
All studied properties	0.001	0.002	0.029

3. Results and discussion

3.1. Identification of soil quality indicators

Sampling depth (0–5 and 5–15 cm) and management practices (tillage and residue management) significantly affected the physical, chemical and biological properties evaluated individually and collectively in this study (Table 2). There was a significant management × depth interaction for chemical ($P < 0.10$) and biological parameters. The ANOVA also identified significant management × depth interactions for several individual parameters (Table 3). Therefore, factor analysis to select SQIs was performed separately for the two depth increments.

Individual ANOVAs also indicated that management factors affected several of the physical and biological parameters studied, and total N (Table 3). Soil measurements that were not significantly affected by management at either depth (texture parameters, P, K and $CaCO_3$ concentrations, pH, EC, and NO_3^-, NH_4^+ and organic C concentrations after 28 days of incubation (CO_2-C_{28d})) were excluded from further consideration as possible

Table 3
Results of the analysis of variance (ANOVA) for physical, chemical, organic matter and biological soil properties.

Soil properties	Number of studied depths	R^2	Factor		
			Management (*M*) (tillage + residue)	Depth (*D*)	$M \times D$
ANOVA *P*-value					
Physical					
Bulk density (ρ_b)	2	0.72	<0.0001	0.03	0.18
MWD_w	2	0.78	<0.0001	<0.0001	0.07
MWD_d	2	0.58	0.005	0.22	0.02
MWD_w/MWD_d	2	0.74	<0.0001	0.001	0.48
PR	2	0.85	<0.0001	0.001	0.99
Coarse sand (%)	2	0.29	0.39	0.06	0.78
Fine sand (%)	2	0.14	0.39	0.71	0.97
Silt (%)	2	0.24	0.27	0.36	0.63
Clay (%)	2	0.16	0.50	0.29	0.89
K_{fs}	1	0.29	0.25	NA	NA
Chemical					
Total N	2	0.89	<0.0001	<0.0001	0.48
P	2	0.51	0.26	0.001	0.53
K	2	0.63	0.89	<0.0001	0.46
$CaCO_3$	2	0.16	0.53	0.84	0.47
pH	2	0.22	0.67	0.97	0.23
EC	2	0.59	0.54	0.07	0.005
Organic matter and biological					
SOC	2	0.83	0.013	<0.0001	0.008
C/N	2	0.71	0.012	0.003	<0.0001
POM-C	2	0.95	<0.0001	<0.0001	0.004
POM-C/N	2	0.48	0.04	0.009	0.56
CO_2-C_{28d}	1	0.37	0.07	NA	NA
CO_2-C_{14d}	1	0.49	0.015	NA	NA
$NH_{4,28d}^+$	1	0.15	0.84	NA	NA
$NO_{3,28d}^-$	1	0.53	0.12	NA	NA

Table 4
Correlation among measured soil attributes considered for FA in the 0–5 cm depth across all management treatments.

	ρ_b	MWD_w	MWD_d	MWD_w/MWD_d	PR	SOC	Total N	C/N	POM-C	POM-C/N
Bulk density (ρ_b)	1									
MWD_w	0.735**	1								
MWD_d	0.506**	0.592**	1							
MWD_w/MWD_d	0.708**	0.975***	0.413*	1						
PR	0.846***	0.783***	0.514**	0.749***	1					
SOC	0.313	0.615**	0.414*	0.590**	0.504**	1				
Total N	0.262	0.487**	0.332	0.440**	0.614**	0.611**	1			
C/N	0.129	0.452**	−0.216	0.542**	0.350*	0.350*	0.371*	1		
POM-C	0.271	0.587**	0.263	0.575**	0.449**	0.825***	0.500**	0.466**	1	
POM-C/N	−0.099	−0.077	0.165	−0.129	−0.161	0.320	−0.281	−0.275	0.371*	1
CO_2-C_{14d}	−0.006	0.219	−0.051	0.257	−0.010	0.480**	0.129	0.103	0.531**	0.059

* Correlation is significant at $P < 0.10$.
** Correlation is significant at $P < 0.05$.
*** Correlation is significant at $P < 0.01$.

candidates for a minimum data set. Furthermore, SOC, total N and the C/N ratio were excluded for the 5–15 cm depth since tillage and residue management did not have any significant effects at this depth (data not shown).

3.1.1. 0–5 cm depth

Development of a correlation matrix for the 11 soil attributes selected for the 0–5-cm depth increment to represent soil physical and biological properties (determinant < 0.0001) showed several correlations among the variables with significant relationships ($P < 0.05$) being identified for 26 of the 55 soil attribute pairs (Table 4). The highest correlations found were for SOC vs. POM-C, ρ_b vs. PR and MWD_w vs. PR (positive correlation). This implies that for the soil at this site, the observed changes in SOC concentrations are related to changes in the POM fraction and that differences found in aggregate stability to water were related to the consolidation of the soil as a whole. The observation that POM is a driving variable for changes in SOM in semi-arid Mediterranean soils has also recently been shown by Martinez-Mena et al. (2008). They observed that changes in SOC within three different Calcisols in SE Spain in response to land use were primarily evidenced by changes in POM.

A principal components analysis identified three factors (F1, F2 and F3) with eigenvalues >1 for the 0–5-cm depth. These factors explained >78% of variability in measured soil properties (Table 5). Considering the individual soil attributes, these three factors explained >75% of variance for 11 soil attributes with the exception being for total N and CO_2-C_{14d} (Table 6). Those two parameters were thus considered to be less important for soil quality evaluation in this study (Brejda et al., 2000; Shukla et al., 2006).

Factor scores were calculated using the resulting component score coefficient matrix (data not shown) and tested for significant differences in response to tillage and crop residue management (Table 6). Only F1 and F2 showed significant differences for this soil depth (0–5 cm), so only those soil properties with high loadings for these factors were considered for SQI selection. F1 had high positive loadings (>0.75, Table 6) from ρ_b, MWD_d, MWD_w, MWD_w-to-MWD_d ratio, and PR. We named this factor "Near-surface Physical Status" because it primarily explained variations in aggregate stability, porosity and the soil physical resistance (i.e., soil structure attributes). F2 had the highest positive loadings (>0.70, Table 6) from SOC, POM-C and CO_2-C_{14d}. This factor was thus named "Near-surface Organic Matter Status" as it grouped soil attributes related to the organic matter and its bioavailability. All or some of these parameters have been repeatedly selected in similar soil quality assessments under different climatic and agronomical conditions (Wander and Bolero, 1999; Wienhold et al., 2004; Giuffré et al., 2006; Govaerts et al., 2006).

In contrast to some other similar studies (e.g. Andrews et al., 2002a; Shukla et al., 2006), this study showed a clear separation between physical and biochemical parameters. Loadings of the studied physical parameters on F2 (Near-surface Organic Matter Status) were low (Table 6). This can be in part attributed to the nature of the studied soils, where development of soil structure and its stabilization are likely to be related not only to the organic fraction, but also to other components of the mineral fraction such as carbonates. Also, differences in the response of soil physical and biological attributes to stubble burning may be responsible for this separation.

Table 5
Eigenvalue, proportion and cumulative variance explained by factor analysis using the correlation matrix of the standardized data of soil attributes at 0–5 and 5–15 cm depths.

Factors	Eigenvalue	Proportion (%)	Cumulative (%)
0–5 cm			
F1	5.23	47.5	47.5
F2	1.82	16.5	64.1
F3	1.55	14.1	78.2
5–15 cm			
F4	2.70	38.6	38.6
F5	2.04	29.2	67.8
F6	1.24	17.8	85.6

Only factors with eigenvalues > 1 are shown.

Table 6
Proportion of variance explained using varimax rotation for each of the retained factors and communalities for the selected soil attributes for the 0–5 cm depth, and effect of management on factor scores for the studied management systems ($P < 0.05$).

	F1	F2	F3	Communality
Soil properties				
ρ_b	0.887	−0.046	0.038	0.79
MWD_w	0.857	0.356	0.200	0.90
MWD_d	0.765	0.034	−0.440	0.78
MWD_w/MWD_d	0.775	0.379	0.324	0.85
PR	0.899	0.128	0.228	0.88
SOC	0.449	0.818	−0.044	0.87
Total N	0.487	0.360	0.384	0.51
C/N	0.149	0.403	0.764	0.77
POM-C	0.339	0.888	0.021	0.90
POM-C/N	−0.092	0.422	−0.780	0.79
CO_2-C_{14d}	−0.104	0.733	0.052	0.55
Management effect				
ANOVA *P*-value	<0.0001	0.002	0.365	
Mean scores				
NT	0.45 b	1.19 c	−0.70	
NTSB	1.29 c	−0.56 ab	0.54	
CT	−0.86 a	−0.90 a	−0.08	
MT	−0.88 a	0.28 bc	0.24	

Table 7
Correlation among measured soil attributes considered for FA in the 5–15 cm depth across all management treatments.

	ρ_b	MWD_w	MWD_d	MWD_w/MWD_d	PR	POM-C
Bulk density (ρ_b)	1					
MWD_w	0.238	1				
MWD_d	−0.023	0.430**	1			
MWD_w/MWD_d	0.281	0.897***	0.001	1		
PR	0.477**	0.588**	−0.011	0.694**	1	
POM-C	0.091	0.079	0.292	0.082	−0.037	1
POM-C/N	0.491**	−0.074	0.217	−0.205	0.150	0.787***

** Correlation is significant at $P < 0.05$.
*** Correlation is significant at $P < 0.01$.

The two soil attributes with highest loadings in F1 and F2 were PR and POM-C, respectively. MWD_w and ρ_b had loadings for F1 within 10% of that of PR, while SOC had a similar loading as compared to POM-C within F2. Redundancy analysis confirmed a significant correlation among the variables within each factor. Following the criterion for selecting soil attributes with the highest sum of correlation coefficients (absolute values, Table 4) as the most appropriate SQI (Andrews and Carroll, 2001; Andrews et al., 2002b), PR and SOC and POM-C were selected as the most sensitive near-surface SQI for the studied soil.

Penetration resistance is a known limiting factor of the soil physical quality, and it has been proven to be a sensitive SQI in other SQ studies using factor analysis in semi-arid rainfed cereal land (Govaerts et al., 2006). In our study, PR was correlated to MWD_w indicating that it did not increase due to disaggregation of the soil structure. POM has been described as an early soil quality indicator in many different agricultural soils (Cambardella and Elliot, 1992; Gregorich et al., 1994; Aoyama et al., 1999). Our results also indicate that for semi-arid, carbonate-rich soil, POM can be used to monitor soil quality for long-term crop production.

3.1.2. 5–15 cm depth

A significant correlation matrix (determinant <0.0001), similar to that developed for the surface layer, was developed using nine soil attributes for the 5–15 cm depth increment. It identified strong correlations among several variables (Table 7), but statistically significant correlations were found for only 7 of the 21 possible pairs at this depth. Similar to the matrix for the 0–5 cm depth, the highest correlations were found for SOC vs. POM-C (positive correlation) and for PR vs. MWD_w/MWD_d.

Principal component analysis identified three Factors (F4, F5 and F6) with eigenvalues >1. These three factors explained >85% of variability in measured soil properties (Table 5). Factor F4 had high positive loadings (>0.85, Table 8) from MWD_w, MWD_w-to-MWD_d ratio, and PR. It was named "Sub-surface Physical Status" because it explained variations in wet aggregate stability and porosity (i.e., soil structure attributes) at this depth. Factor F5 received the highest loadings from parameters related to soil organic matter and was named "Sub-surface Organic Matter Status." Factor F6 had a significant positive loading (0.867, Table 8) from only MWD_d, therefore, we did not use it for our analysis since it added only one additional soil measurement.

Table 8
Proportion of variance explained using varimax rotation for each of the retained factors and communalities for the selected soil attributes for the 5–15 cm depth ($P < 0.05$).

	F4	F5	F6	Communality
Soil properties				
ρ_b	0.512	0.577	−0.396	0.75
MWD_w	0.869	−0.061	0.461	0.97
MWD_d	0.093	0.191	0.867	0.80
MWD_w/MWD_d	0.936	−0.176	0.081	0.91
PR	0.856	0.164	−0.176	0.79
POM-C	−0.096	0.790	0.398	0.79
POM-C/N	−0.037	0.983	0.045	0.97
Management effect				
ANOVA *P*-value	<0.0001	0.079	NA	
Mean scores				
NT	0.34 c	1.07 b	NA	
NTSB	1.21 d	−0.41 a	NA	
CT	−1.28 a	−0.20 a	NA	
MT	−0.27 b	−0.46 a	NA	

Similar to the approach used for the 0–5 cm depth, scores for factors F4 and F5 were calculated and tested for significant differences due to management (Table 8). Results differed from those obtained for the surface 5 cm as only F4 showed significant differences at $P < 0.05$. Differences for F5 were only significant at $P < 0.10$. This result, together with the absence of differences in the SOC content at the 5–15 cm depth, indicates that differences in the organic matter status due to management in this soil layer were less important than differences in the physical properties.

The two soil attributes with highest loadings in F4 and F5, were the MWD_w-to-MWD_d ratio and POM-C/N, respectively. These factors can thus be considered sensitive SQI for this depth in the studied soil. The MWD_w-to-MWD_d ratio is a well-known index for aggregate stability (Lehmann et al., 2001; Franzluebbers, 2002). In the studied soil, this ratio had an important loading in F1, and in all cases it was <1 (data not shown) indicating a lower soil resistance to disruption by water than mechanical stress. The C/N ratio is another indicator of POM quality (Wander and Bidart, 2000; Marriott and Wander, 2006), and it showed a small loading in F2. This suggests that changes induced in the organic matter fraction at this depth affected the quality of particulate organic matter more than its amount.

3.2. Soil quality evaluation

The evaluation of soil quality following factor analysis was accomplished in two steps. We first used the scores of F1, F2, F4 and F5 to identify homogeneous groups of indicators among the studied parameters. We then studied the correlation of factors F1 and F2 with some well-known SQI for the soil in this area. We chose SOC stratification because it has been described as a good indicator for crop growth under NT (Franzluebbers, 2002; Moreno et al., 2006). Soil earthworm activity and water retention capacity were also chosen because they have been observed to correlate with higher crop yields under NT at this site (Bescansa et al., 2006a; Virto et al., 2007).

Mean scores for F1 and F2 (Table 6 and Fig. 1) indicated that soil physical status (F1) for the 0–5-cm depth was similar under CT and MT but different from NT and NTSB. The organic matter status (F2) was significantly different between NT and CT, with NTSB and MT having intermediate scores for this factor. The 0–5 cm soil layer under NTSB had an intermediate behavior between NT and CT. These results match those found by Virto et al. (2007), in that

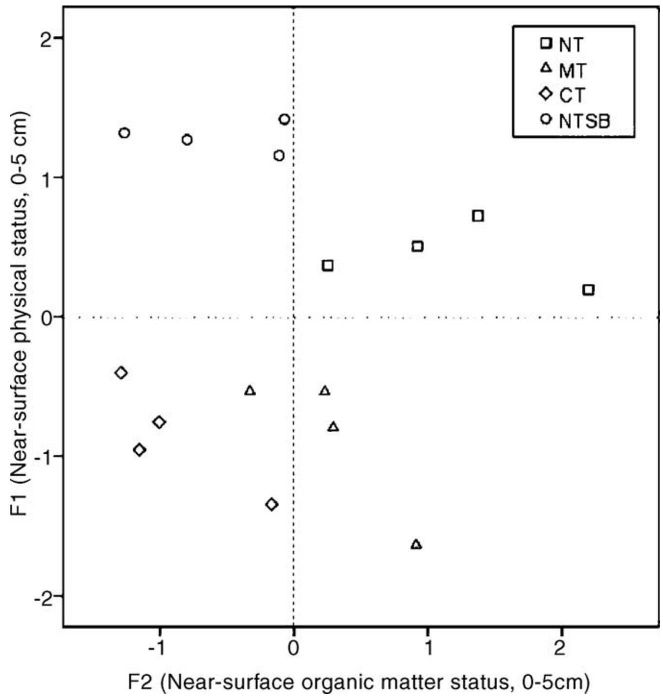

Fig. 1. Near-surface (0–5 cm) relationship between soil quality assessment factors selected through principal component analysis. NT: no-till; MT: minimum tillage; CT: conventional tillage; NTSB: no-till with stubble burning.

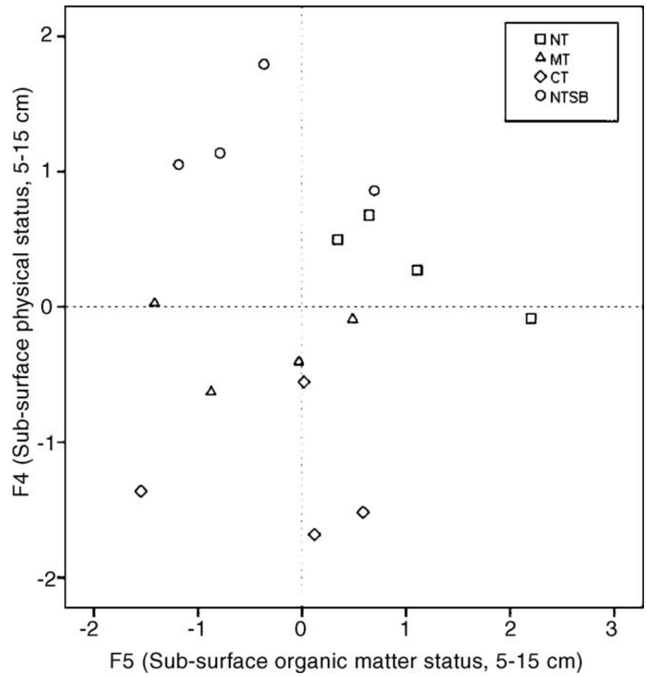

Fig. 2. Sub-surface (5–15 cm) relationship between soil quality assessment factors selected through PCA analysis. NT: no-till; MT: minimum tillage; CT: conventional tillage; NTSB: no-till with stubble burning.

stubble burning seems to affect organic matter quality within the upper layer of the soil without degrading its physical qualities. These differences among treatments also indicate that attention must be paid both to soil physical and organic matter attributes when comparing soil quality for different tillage and residue management practices in this area.

Correlation analysis of F1 and F2 with the well-known SQI showed that F1 was positively correlated to AWR (Pearsons' coefficient = 0.560, $P < 0.05$) and earthworm density (Pearsons' coefficient = 0.444, $P < 0.10$), while the organic matter stratification ratio was significantly correlated to F2 (Pearsons' coefficient = 0.755, $P < 0.01$). The correlation of F1 to water retention showed that the soil physical quality in the 0–5 cm depth increased as tillage decreased, especially since water availability is the most limiting crop growth factor in the area.

Considering that the soil attribute with the highest loading in F1 was PR, the correlation with earthworm density is important because it indicates that the observed positive correlation of PR and ρ_b (Table 4) did not interfere with earthworm activity. This is considered important because earthworm activity is often an important adequate indicator of not only the biological status of the soil under different tillage practices (Kladivko, 2001) but also for soil physical quality in semi-arid areas such as the one studied (Buckerfield, 1992).

With regard to soil organic matter, Franzluebbers (2002) established the significance of organic matter stratification for the evaluation of soil quality in NT land. However, he acknowledged that the applicability for using the ratio as a SQI needed to be tested in different agroecological zones. Our results indicated a significant correlation between this SQI and the near-surface organic matter status factor (F2), and that NT (the treatment with the highest scores for F2) was the most favorable with regard to soil organic matter quality in this soil. This result agrees well with data recently reported by Álvaro-Fuentes et al. (2008) for similar arid and semi-arid Mediterranean agricultural soils in NE Spain.

Similar to the 0–5 cm layer, differences within the 5–15 cm depth with respect to soil physical status (F4) were similar for NT and NTSB, but different from the treatments involving tillage (Table 8 and Fig. 2). However, unlike the surface measurements (0–5 cm), scores for F5 (Sub-surface Organic Matter Status) were scattered and only NT differed clearly form the other three treatments (Fig. 2). It seems that changes in the organic fraction induced tillage and crop residue management were more important within the 0–5 cm depth than for the 5–15 cm depth. Considering that the most sensitive SQI selected at this depth for organic matter quality assessment was POM-C/N, these results also indicate that stubble burning induced changes in the POM quality. Overall, POM quality was similar under CT and MT, but different from that under NT wit no stubble burning.

In summary, the highest soil quality was found under NT for both sampling depths. This is also the treatment with highest scores in all the four factor analysis groupings. Furthermore, comparing Figs. 1 and 2, we suggest that near-surface (0–5 cm) measurements were more useful for finding differences in soil quality among treatments than the deeper (5–15 cm) increment.

4. Conclusions

Multivariate and factor analysis proved to be useful for selection of appropriate SQI for Mediterranean semi-arid rainfed cereal cropland. Penetration resistance, POM-C and SOM proved to be the most sensitive near-surface (0–5 cm) SQI for this agrosystem in our study. Aggregate stability and POM quality were the most sensitive SQI for the 5–15 cm depth. These indicators should thus be included in any minimum data set used for soil quality assessment for rainfed cereal production in the region.

Factors obtained by PCA were positively correlated to the soil water retention ability, earthworm activity and organic matter stratification. This allowed for a comparative soil quality evaluation for different tillage and residue management practices that would be of great use for to demonstrate the usefulness of the newly found SQI for the evaluation of the effect of different management practices in this type of agrosystems in the region.

Our results showed that the implementation of NT techniques on Mediterranean semi-arid land had positive effects on soil quality. Residue burning under NT was seen to have more influence on the topsoil physical status than on other chemical and biological properties.

Considering the site-specificity of soil quality evaluation, further work is needed to better determine the sensitivity of our selected SQI for assessment of soil quality within other soil types in the area and for similar soils in other areas. These results are a promising first step towards the evaluation of these and other indicators in studies comprising more diverse soil management systems for rainfed cereal production, and towards more ambitious soil quality assessment programs in the region.

Acknowledgements

This research was supported by the Gobierno de Navarra and the Spanish Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria, INIA (Acción movilizadora de "Sumideros Agroforestales de Efecto Invernadero, Ref. SUM2006-00012-00-00). The technical assistance of the Instituto Técnico y de Gestión Agrícola (ITGA) is acknowledged as well. The authors thank the USDA-ARS National Soil Tilth Laboratory for the assistance during the research internship of Maria Jose Imaz in their laboratories. Ana Vicente (Gobierno de Navarra) is particularly thanked for her valuable help in providing crops surfaces and yield data.

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